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An Assessment of Potential Oil Spill Damage to Salt Marsh Habitats and Fishery Resources in Galveston Bay, Texas

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We sampled nekton, benthic infauna, and sediments in salt marshes of upper Galveston Bay, Texas to examine relationships between habitat use and sediment hydrocarbon concentration. Most marsh sediment samples were contaminated with relatively low concentrations of weathered petroleum hydrocarbons. We found few statistically significant negative relationships between animal density and hydrocarbon concentration (6 of 63 taxa examined using simple linear regression). Hydrocarbon concentration did not contribute significantly to Stepwise Multiple Regression models we used to explore potential relationships between animal densities and environmental parameters; in most cases where hydrocarbon concentration was an important variable in the models, the relationship was positive (i.e., animal densities increased with hydrocarbon concentration). Low hydrocarbon concentrations in sediments of upper Galveston Bay marshes could have contributed to our results either because levels were too low to be toxic or levels were toxic but too low to be detected by most organisms. Published by Elsevier Science Ltd.

Keywords: benthic infauna; estuary; fisheries; nekton; salt marsh; sediment hydrocarbon concentration.

Introduction

The northern Gulf of Mexico supports some of the most productive fisheries in the US, and most species use estuarine nursery areas during their early life. While residing in estuaries, the young of these species, including brown shrimp *Farfantepenaeus aztecus* (formerly *Penaeus aztecus*, Pérez Farfante and Kensley, 1997), white shrimp *Litopenaeus setiferus* (formerly *Penaeus setiferus*, Pérez Farfante and Kensley, 1997), blue crab *Callinectes sapidus*, spotted seatrout *Cynoscion nebulosus*, southern flounder *Paralichths lethostigma*, and red drum *Sciaenops ocellatus*, use the flooded marsh surface, and especially the marsh edge, in high densities (Zimmerman and Minello, 1984; Thomas, 1989; Minello and Zimmerman, 1991; Rozas and Zimmerman, 2000). Moreover, salt marshes provide habitat for many species important in the food web supporting both recreational and commercial fisheries.

Many estuaries in the northern Gulf of Mexico are also centers for the petrochemical industry, and oil spills are not uncommon. Such spills can potentially cause great damage to salt marsh habitats. Oil has been shown to have extensive negative effects on marsh vegetation (Mendelssohn *et al.*, 1990; Webb and Alexander, 1991; Pezeshki and DeLaune, 1993), but the effect of oil on the use of salt marsh by fishery species has not been examined.

Densities of animals in salt marshes may be reduced by acute, short-term toxic effects of crude oil that sharply increase mortality rates (Anderson *et al.*, 1974; Sanders *et al.*, 1980; McDonald *et al.*, 1991; Nance, 1991; Widbom and Oviate, 1994) or cause avoidance by mobile organisms (Moles *et al.*, 1994). But oil can persist in marsh sediments for many years (Teal and Howarth, 1984; DeLaune *et al.*, 1990) and may continue to affect habitat use. Long-term effects of marsh contamination may be even more damaging to fishery resources than short-term effects.

Our objective was to examine the relationship between petroleum in marsh sediments and use of the marsh surface by estuarine species. Specific goals were to: (1) identify estuarine species and quantify animal densities in the marshes of upper Galveston Bay, an area that has episodically received oil from spills in the San

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Jacinto River and the Houston Ship Channel and (2) examine the relationships between the presence of hydrocarbons in marsh sediments and the density of infauna and nekton on the marsh surface (We tested the null hypothesis that there is no relationship between sediment hydrocarbons and use of the marsh surface by infauna and nekton.) We also discuss factors that affect marsh recovery after an oil spill, and a method for estimating recovery rates of oiled marshes in our study area.

Study Area

Our research was conducted in upper Galveston Bay along the eastern shores of Hog and Atkinson Islands, and the shoreline of Tabbs Bay, from the mouth of the San Jacinto River to Houston Point (Fig. 1). At least three oil spills have occurred in the area within the last decade. The *Apex* oil spill occurred in July 1990 in Galveston Bay along the Houston Ship Channel, and oil from this spill came ashore near Cedar Point. In October 1994, three pipelines crossing the San Jacinto River ruptured, releasing unleaded gasoline, home heating oil, and Arabian light crude oil into the river (Baytown Spill), with much of the gasoline and fuel oil burned in the river. The hydrocarbons that did not burn (a mixture of diesel and crude oil) came ashore along the Houston Ship Channel and in upper Galveston Bay along the eastern shores of Hog Island and Atkinson Island. In May 1996, a barge being transported through the ship channel buckled near Morgan's Point, releasing fuel oil. Fortunately, little of the oil from this spill reached marshes in the area. Generally, marshes in the study area were allowed to recover naturally, but little is known of the effect of these spills on marsh utilization. In addition to oil spills, chronic nonpoint pollution entering the study area in urban runoff is a stressor, but again, degree of injury is not known.

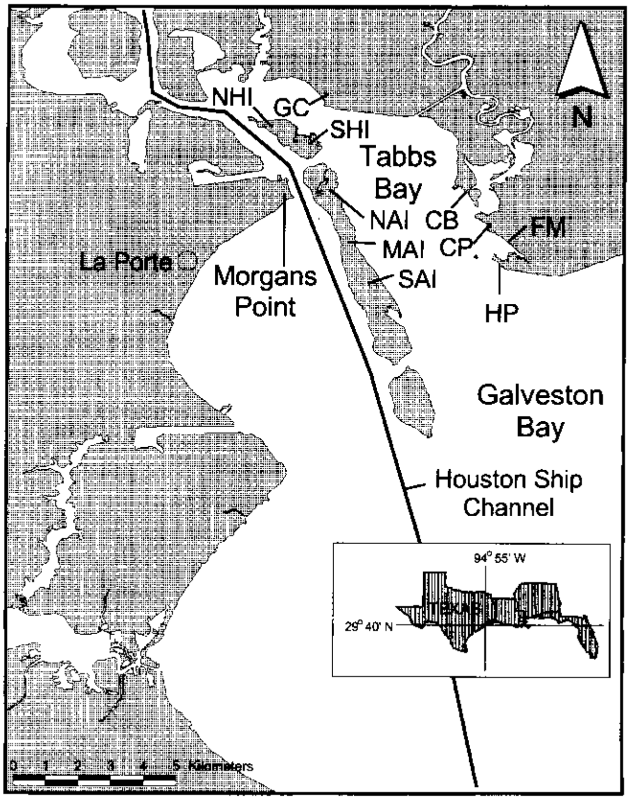

Fig. 1 Map of the study area in upper Galveston Bay. Samples were collected at north (NAI), middle (MAI), and south (SAI) Atkinson Island, north (NHI) and south (SHI) Hog Island, Goose Creek (GC), Cedar Bayou (CB), Cedar Point (CP), Houston Point (HP), and the fringing marsh (FM) between CP and HP. Within each of the 10 locations, five sites were sampled in September 1995 and May 1996. The San Jacinto River and Houston Ship Channel enter upper Galveston Bay northwest of Hog Island.

Methods

The spring and fall seasons are periods when many species of nekton (fishes and decapod crustaceans) are utilizing marsh surfaces in Galveston Bay (Zimmerman and Minello, 1984). Over a period of 9 d in fall (19–27 September 1995) and 4 d in spring (7–10 May 1996), we collected 100 samples of nekton, infauna, and petroleum hydrocarbons in *Spartina alterniflora* at the marsh edge (marsh–water interface) from 10 locations along the shoreline, Atkinson Island to Houston Point in upper Galveston Bay (Fig. 1). We used a stratified random sampling design to insure that sample locations included marshes heavily oiled in the past as well as areas that are relatively clean. Ten strata were sampled, North Atkinson Island, Middle Atkinson Island, South Atkinson Island, North Hog Island, South Hog Island, the shoreline of Tabbs Bay near Goose Creek, Cedar Bayou, Cedar Point, fringing marsh between Cedar Point and Houston Point, and Houston Point. During each season, sample sites were randomly selected along shorelines at each location.

Sampling design

Samples of nekton within the vegetation were collected at high tide with a 1.14-m diameter cylinder dropped from a boom mounted on a shallow-draft aluminum boat (see Zimmerman *et al.*, 1984). Two persons positioned the cylinder over a sample site by slowly pushing from the boat's stern. When released from the boom, the cylinder rapidly enclosed a 1.0-m^2 sample area. Use of this procedure minimized disturbance to the sample site.

After a drop, we measured water temperature and dissolved oxygen in the sampler with a YSI Model 51B meter. We determined salinity with an American Optical temperature-compensated refractometer. Turbidity was measured in the laboratory (HF Instruments nephelemeter) from a water sample collected at the sample site. We estimated water depth at each sample site by averaging five depths measured within the sampler. Marsh elevation was determined by relating the average water depth measured at each site with concurrent water-level data from a tide gauge located at Morgan's Point (NOS Station I.D. = 87700613). Distance to edge was measured as the shortest distance between enclosure and shoreline.

Spartina stems in the sampler were clipped at sediment level, counted, and removed from the cylinder. Four 5-cm diameter cores were taken randomly inside the cylinder, and benthic infaunal densities determined from a pooled sample consisting of three of these cores; we determined sediment grain size and sediment organic content from the fourth core. Infaunal samples were washed on a 0.5-mm mesh sieve, and materials retained fixed with 10% formalin, stained with Rose Bengal. In the laboratory, organisms were separated from detritus and plant parts and identified. Amphipods, tanaids, and polychaete worms were identified to species, and the remaining organisms to the lowest feasible taxon. We used the method described by Folk (1980) to determine proportions of sand, silt, and clay in the sediment samples. Sediment organic content was determined by combusting a 2–5 g sediment subsample in a muffle furnace at 550°C for 1 h (Dean, 1974).

At each sample site, we took an additional sediment core (2.5-cm diameter, 5-cm deep) adjacent to each infaunal core location, and pooled these three sediment samples for hydrocarbon analysis. The pooled samples were placed into a pre-cleaned 125-ml clear glass jar, covered with a Teflon-lined lid, and frozen until analysis.

We captured natant macrofauna trapped in the drop sampler with dip nets and by pumping the water out of the enclosure through a 1-mm mesh net. When the sampler was completely drained, we removed remaining animals on the bottom by hand. Samples were preserved in formalin with Rose Bengal and returned to the laboratory for processing where we sorted samples and identified macrofauna to species or lowest feasible taxon.

Analytical methods for hydrocarbon analyses

Sediment samples were analyzed for petroleum hydrocarbons using gas chromatography/mass spectrometry (GC/MS) by personnel at the Institute for Environmental Studies (IES), Louisiana State University. GC/MS has previously been used by the IES for both oil spill response activities and fate and effects studies (Reed, 1977; Boehm and Farrington, 1984; Kennicutt, 1988; Sauer and Boehm, 1991; Hostettler *et al.*, 1992; Henry and Overton, 1993; Hoff *et al.*, 1993; Sauer *et al.*, 1993).

General approach. Crude oil is a complex mixture of compounds that cannot be completely resolved by gas chromatography, but by using a mass spectrometer in conjunction with high resolution chemical separation (the GC), specific target compounds can be discriminated from the bulk oil. Typically for crude oils, the target aromatic hydrocarbons represent less than 2% of the bulk oil composition by weight, and many of the target analytes are present at the low ppm level in whole oil. The method used in this study was designed to accomplish the following: detect the presence of oil, provide compound specific quantification of target compounds, and provide data applicable to source-identification. Guidelines established for legally defensible data as outlined by Sauer and Boehm (1991) are also incorporated in the analytical method used.

GC/MS provides gross total petroleum hydrocarbon (TPH) values, highly selective source-fingerprinting information, and compound-specific quantitative results for target aromatic and aliphatic hydrocarbons (Butt *et al.*, 1986; Burns, 1993). Target aromatic hydrocarbons were selected not only for their applicability to source-identification, but also their association with the toxicity of spilled oil. These same target compounds are useful for monitoring oil weathering and biodegradation. Petrogenic (oil or petroleum derived) and pyrogenic (combustion derived) aromatic hydrocarbons are monitored as well as alkanes, sulfur heterocycles, sterane, triterpanes, and hopanes. For this study, the GC/MS was operated in both a rapid screen mode from which TPH values were determined and in a high resolution mode for quantitative analyses of specific aromatic hydrocarbons in selected samples.

Sample analyses. Sediment samples were extracted using dichloromethane (DCM) followed by silica-gel cleanup prior to analysis. Sample preparation, extraction, and GC/MS analyses were similar to Lauenstein and Cantillo (1993). The GC/MS technique was modified to target petroleum sourced hydrocarbons as identified in Roques *et al.* (1994). For all analyses, a Hewlett–Packard 5890 GC configured with a DB-5 (J&W Scientific) column directly coupled to a Hewlett–Packard 5971 MS was used.

Each sample aliquot was injected into the GC configured as above, but the system was operated in the full scanning mode (m/e 45–450), and a temperature program designed to reduce the chromatographic program time to only 30 min was employed. The entire chromatogram was integrated and quantified using response factors derived from either diesel fuel or mineral oil depending on which best fit the chromatographic profile. This difference was important to the quantification of TPH since the response factor varied significantly.

We determined two TPH fractions, i.e., mid-range petroleum hydrocarbons (MPH, diesel-like range of constituents) and heavy-range petroleum hydrocarbons (HPH, mineral oil range of constituents). Each fraction was quantified and reported individually and as a total. TPH by GC/MS is an effective screening technique since the method can provide both qualitative and quantitative information through interpretation of chromatographic profiles. The suite of semi-volatile petroleum hydrocarbons applicable to this method range between the boiling points of nC-9–nC-35. Differentiation between the MPH and HPH was the cross-over point

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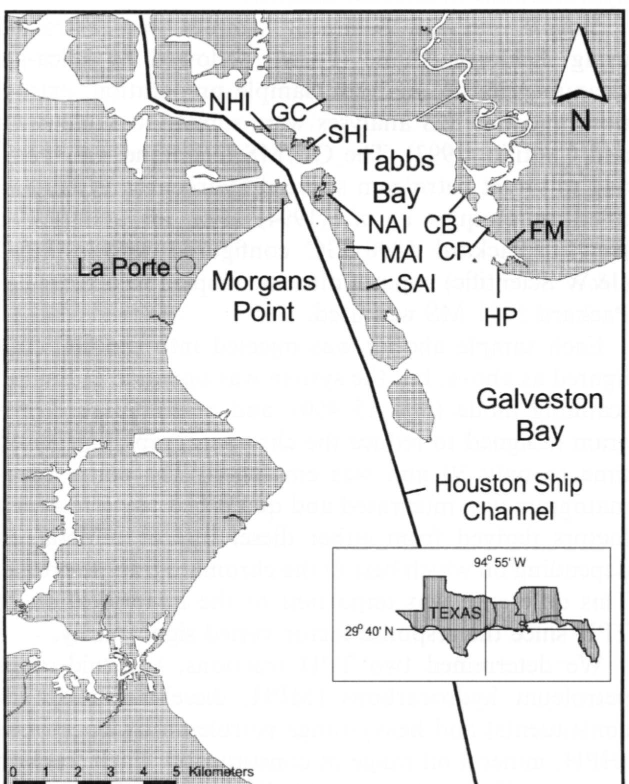

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Statistical analyses

Spring and fall data were analysed separately because many species of animals were only abundant enough to include in the statistical analyses for one season. We tested for differences in TPH and MPH among locations using analysis of variance (ANOVA); to test for differences among sample locations, we used Scheffe's S to control the experimentwise error rate in post hoc comparisons (Day and Quinn, 1989). We tested the null hypothesis that there is no relationship between sediment hydrocarbon concentration and use of the marsh surface by nekton and infauna using two types of analysis. We examined potential relationships between animal abundance and sediment hydrocarbons by regressing densities of abundant organisms against sediment TPH and MPH concentrations and examined scatter plots of the data for nonlinear relationships. We further explored potential relationships between animal density and sediment hydrocarbon concentrations by including 10 independent variables (salinity, distance to edge, water temperature, dissolved oxygen concentration, mean depth, turbidity, stem density, elevation, sediment organic content, and sediment sand content) in addition to either TPH or MPH in a Stepwise Multiple Regression Analysis. Because mean animal densities and mean hydrocarbon values were positively related to the standard deviation, we performed a $\log(x+1)$ transformation on these data prior to statistical analyses. Other variables were not transformed. All tabular and graphical data presented in this paper are untransformed means. We conducted ANOVA's using Super-ANOVA software and regression analyses with StatView (Abacus Concepts, Berkley, CA); an alpha level of 0.05 was considered statistically significant.

Results

We collected a total of 19 species of fishes and 11 species of decapod crustaceans in September 1995, 17 fish species and 14 crustacean species in May 1996 (Table 1). Although most species collected were fishes, decapod crustaceans accounted for the greatest number of organisms in our samples (92.7% and 86.3% of the total in fall and spring, respectively). We also collected five species of molluscs with the drop sampler, but this sampling technique was not designed to quantitatively sample benthic infauna. Therefore, the abundance of molluscs and other benthic taxa were quantified from core collections, and animals other than fishes and decapod crustaceans that were taken with the drop sampler were not enumerated.

In fall, six species numerically dominated the fish assemblage, and accounted for >95% of the total. The most abundant species were naked goby *Gobiosoma bosc*, blackcheek tonguefish *Symphurus plagiusa*, bay anchovy *Anchoa mitchilli*, spotted seatrout *Cynoscion nebulosus*, skilletfish *Gobiesox strumosus*, and striped mullet *Mugil cephalus* (Table 1). Daggerblade grass shrimp *Palaemonetes pugio*, white shrimp *Litopenaeus setiferus*, marsh grass shrimp *P. vulgaris*, blue crab *Callinectes sapidus*, brackish grass shrimp *P. intermedius*, Harris mud crab *Rhithropanopeus harrisii*, and brown shrimp *Farfantepenaeus aztecus* accounted for >99% of the total decapod crustaceans taken in our drop samples (Table 1).

The most abundant fishes in spring (89% of the total) were gulf menhaden *Brevoortia patronus*, blackcheek tonguefish, spot *Leiostomus xanthurus*, bay anchovy,

TABLE 1

Mean density, number m^{-2}, and (S.E., one standard error) of the most abundant fishes and decapod crustaceans collected in shoreline *Spartina* marsh of upper Galveston Bay in September 1995 and May 1996.[a]

Species	Mean	S.E.
September 1995		
Fishes (Total = 19 species)		
Naked goby *Gobiosoma bosc*	15.7	(1.68)
Blackcheek tonguefish *Symphurus plagiusa*	1.0	(0.17)
Bay anchovy *Anchoa mitchilli*	0.7	(0.30)
Spotted seatrout *Cynoscion nebulosus*	0.5	(0.11)
Striped mullet *Mugil cephalus*	0.2	(0.09)
Skilletfish *Gobiesox strumosus*	0.2	(0.13)
Total fishes	19.3	(1.80)
Crustaceans (Total = 11 species)		
Daggerblade grass shrimp *Palaemonetes pugio*	108.9	(11.51)
White shrimp *Litopenaeus setiferus*	49.6	(12.11)
Marsh grass shrimp *Palaemonetes vulgaris*	37.3	(6.36)
Blue crab *Callinectes sapidus*	20.7	(2.77)
Brackish grass shrimp *Palaemonetes intermedius*	16.8	(2.28)
Harris mud crab *Rhithropanopeus harrisii*	8.1	(1.57)
Brown shrimp *Farfantepenaeus aztecus*	2.9	(0.60)
Total Crustaceans	246.1	(21.09)
May 1996		
Fishes (Total = 17 species)		
Gulf menhaden *Brevoortia patronus*	4.9	(3.99)
Blackcheek tonguefish *Symphurus plagiusa*	2.0	(0.46)
Spot *Leiostomus xanthurus*	1.6	(0.31)
Bay anchovy *Anchoa mitchilli*	0.8	(0.39)
Atlantic croaker *Micropogonias undulatus*	0.7	(0.31)
Total fishes	11.3	(4.06)
Crustaceans (Total = 14 species)		
Daggerblade grass shrimp *Palaemonetes pugio*	39.8	(5.72)
Palaemonetes spp. Postlarvae	8.7	(3.12)
Blue crab *Callinectes sapidus*	6.4	(0.62)
Brown shrimp *Farfantepenaeus aztecus*	5.8	(1.39)
Harris mud crab *Rhithropanopeus harrisii*	3.5	(1.18)
Gulf grassbed crab *Dsypanopeus texana*	1.6	(0.76)
Brackish grass shrimp *Palaemonetes intermedius*	1.3	(0.40)
Lesser blue crab *Callinectes similis*	1.2	(0.32)
Atlantic mud crab *Panopeus herbstii*	0.5	(0.37)
Total Crustaceans	71.1	(7.98)

[a] Each mean is estimated from 50 samples, five samples taken at each of 10 locations. The total number of species collected in each major taxonomic category also is given.

and Atlantic croaker *Micropogonias undulatus*. Dominant crustacean taxa in spring, accounting for 97% of the total, were daggerblade grass shrimp, blue crab, brown shrimp, Harris mud crab, *Palaemonetes* spp. postlarvae, gulf grassbed crab *Dsypanopeus texana*, brackish grass shrimp, lesser blue crab *Callinectes similis*, and Atlantic mud crab *Panopeus herbstii*.

Numerically dominant infaunal taxa taken from the marsh included annelids, small crustaceans, and molluscs (Table 2). The most numerous annelid taxa included oligochaetes and the polychaetes *Polydora ligni*, *Streblospio benedicti*, *Nereis succinea*, *Mediomastus* spp., *Capitella capitata*, *Laeonereis culveri*, *Hobsonia gunneri* (fall), and *Eteone heteropoda* (spring). Dominant crustaceans were *Corophium* spp., *Hargaria rapax*, *Cassidinidea ovalis*, *Gammarus macronatus* (spring), and *Grandidierella bonneroides* (spring). Most molluscs collected consisted of *Texadina sphinctostoma* (fall) and *Geukensia demissa* (spring).

Physical characteristics of marsh sample sites are shown in Table 3. Mean salinities were generally higher in spring (range = 21.2–23.4‰) than fall (range = 13.4–16.6‰). Sample sites were all near the marsh shoreline (average distance ranged from 0.1 to 0.7 m) in both seasons, and mean dissolved oxygen concentrations at all marsh locations were above 5 and 4 ppm in fall and spring, respectively. The ranges in mean water depth and mean elevation among locations in fall were 32 and 26 cm, respectively. In spring, the range in mean water depth (21 cm) was less than in fall, although the range in mean elevation (32 cm) was higher. Sediments were composed mostly of sand at North Atkinson Island and South Hog Island, and chiefly silts and clays at Goose Creek and Cedar Point. The grain size of sediments at other locations was more evenly distributed between coarse (sand) and fine (silt, clay) particles. Cedar Point sediments had the highest proportions of organic material.

Almost all marsh sediment samples were contaminated with petroleum hydrocarbons, but total petroleum hydrocarbon (TPH) concentrations were relatively low in most samples; approximately 75% contained TPH concentrations < 200 ppm each season (Fig. 2). Only

TABLE 2

Mean density, number 60.8 cm^{-2}, and (S.E., one standard error) of numerically abundant infauna collected in shoreline *Spartina* marsh of upper Galveston Bay in September 1995 and May 1996.[a]

Taxon	Mean	S.E.
September 1995		
Annelids		
Oligochaete, unidentified species	47.2	(6.55)
Polydora ligni	31.1	(8.41)
Streblospio benedicti	12.0	(1.86)
Nereis (Neanthes) succinea	11.3	(2.23)
Mediomastus spp.	2.9	(0.58)
Laeonereis culveri	1.4	(0.58)
Capitella capitata	1.1	(0.24)
Hobsonia gunneri	1.0	(0.33)
Total Annelids	108.3	(14.47)
Crustaceans		
Corophium spp.	4.1	(1.72)
Hargaria rapax	3.4	(0.97)
Cassidinidea ovalis	1.3	(0.35)
Total Crustaceans	12.1	(3.27)
Molluscs		
Texadina sphinctostoma	1.5	(0.43)
Total Molluscs	2.1	(0.49)
May 1996		
Annelids		
Oligochaete, unidentified species	24.6	(4.66)
Capitella capitata	14.0	(3.41)
Mediomastus spp.	6.5	(1.48)
Nereis (Neanthes) succinea	6.4	(1.17)
Polydora ligni	5.4	(1.55)
Laeonereis culveri	2.3	(1.10)
Eteone heteropoda	0.8	(0.19)
Streblospio benedicti	0.5	(0.15)
Total Annelids	61.0	(6.44)
Crustaceans		
Hargaria rapax	10.4	(3.62)
Corophium spp.	2.0	(1.05)
Cassidinidea ovalis	1.1	(0.36)
Gammarus macronatus	0.9	(0.28)
Grandidierella bonneroides	0.6	(0.35)
Total Crustaceans	15.4	(5.04)
Molluscs		
Geukensia demissa	0.5	(0.15)
Total Molluscs	0.8	(0.17)

[a] Each mean is estimated from 50 samples, five samples taken at each of 10 locations.

TABLE 3

Environmental characteristics of shoreline marsh of upper Galveston Bay.[a]

Environmental parameter	September 1995		May 1996	
	Mean	S.E.	Mean	S.E.
Salinity (‰)	14.9	(0.15)	22.5	(0.14)
Distance to edge (m)	0.5	(0.06)	0.4	(0.04)
Water temperature (°C)	28.5	(0.35)	28.9	(0.14)
Dissolved oxygen (ppm)	6.8	(0.27)	5.1	(0.14)
Turbidity (FTU)	25.3	(3.29)	83.4	(6.37)
Water depth (cm)	42.2	(1.91)	39.0	(1.41)
Surface elevation (m)	1.62	(0.01)	1.67	(0.02)
Stem density (stems m^{-2})	179	(12.6)	119	(9.4)
Total petroleum hydrocarbons (ppm)	299.6	(155.43)	122.0	(17.39)
Mid-range petroleum hydrocarbons (ppm)	70.6	(47.50)	12.7	(2.75)
Sediment organic content (%)	3.3	(0.48)	2.6	(0.30)
Sediment grain size (%)				
Shell	3	(1.8)	1	(0.2)
Sand	37	(4.0)	41	(3.4)
Silt	29	(3.0)	25	(1.8)
Clay	30	(2.8)	34	(2.3)

[a] Mean and (S.E., one standard error) are given for 12 parameters measured in September 1995 and May 1996. Means were estimated from 50 samples collected each season, five samples taken at each of 10 locations, except Houston Point had 3 missing values for sediment organic content and 1 missing value for sediment grain size in fall.

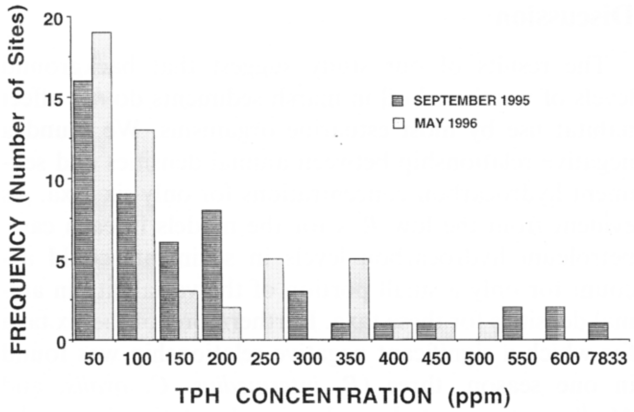

Fig. 2 Concentration frequency plot showing the distribution of TPH values at sample sites among 50-ppm concentration categories in September 1995 and May 1996. Most (77 of 100) sample sites had TPH values <200 ppm.

one site (at North Hog Island in fall) had a TPH level >600 ppm. Sediments at North Hog Island contained the highest average TPH values, but sediment concentrations were highly variable among sites at this location (Table 4). Because of this variability, we detected few significant differences in mean TPH levels among locations. In fall, the mean TPH level at North Hog Island was significantly greater than mean concentrations at Cedar Bayou and South Atkinson Island. In spring, TPH concentrations did not differ significantly among locations. The mid-range petroleum hydrocarbon (MPH) fraction accounted for a small portion of the total hydrocarbons in these samples (Table 4), and MPH concentrations were not significantly different among locations in either season (Scheffe's S; all p's >0.07). Profiles of selected samples analysed by the GC/MS method used to quantify specific aromatic hydrocarbons in sediments show that oils in sediments of our study area were in a highly degraded state (Fig. 3).

We found potential relationships between animal density and TPH concentration for very few animals. The relative lack of significant results was notable, especially considering that at least three significant results would be expected by chance alone from the 63 tests we performed. Of 30 abundant taxa (15 nekton and 15 infauna) examined in fall, only one species (marsh grass shrimp: $R^2 = 0.13$, $d.f. = 1.48$, $p = 0.011$) showed a significant negative relationship with sediment TPH levels. In contrast, significant positive relationships between infaunal densities and TPH concentrations were found for total annelids ($R^2 = 0.13$, $d.f. = 1.48$, $p = 0.010$), total oligochaetes ($R^2 = 0.10$, $d.f. = 1.48$, $p = 0.029$), and *Streblospio benedicti* ($R^2 = 0.12$, $d.f. = 1.48$, $p = 0.013$). Additional regression analyses using MPH rather than TPH resulted in significant negative relationships for marsh grass shrimp ($R^2 = 0.13$, $d.f. = 1.48$, $p = 0.009$) and *C. ovalis* ($R^2 = 0.08$, $d.f. = 1.48$, $p = 0.045$) and a significant positive relationship for *S. benedicti* ($R^2 = 0.10$, $d.f. = 1.48$, $p = 0.023$).

In spring, we examined 33 taxa (16 nekton and 17 infauna) and found a significant negative relationship between TPH concentration and animal density for four taxa: brackish grass shrimp ($R^2 = 0.11$, $d.f. = 1.48$, $p = 0.018$), *Palaemonetes* spp. postlarvae ($R^2 = 0.20$, $d.f. = 1.48$, $p = 0.001$), *E. heteropoda* ($R^2 = 0.08$, $d.f. = 1.48, p = 0.041$), and *Mediomastus* spp. ($R^2 = 0.17$, $d.f. = 1.48$, $p = 0.003$). Significant positive relationships between TPH concentration and animal density were found for the polychaete *P. ligni* ($R^2 = 0.11$, $d.f. = 1.48$, $p = 0.020$), the mollusc *G. demissa* ($R^2 = 0.14$, $d.f. = 1.48$, $p = 0.009$), and total molluscs ($R^2 = 0.13$, $d.f. = 1.48$, $p = 0.010$). Significant relationships between MPH concentration and animal density were negative for brackish grass shrimp ($R^2 = 0.15$, $d.f. = 1.48$, $p = 0.006$), *Palaemonetes* spp. postlarvae ($R^2 = 0.09, d.f. = 1.48, p = 0.031$), *E. heteropoda* ($R^2 = 0.16$, $d.f. = 1.48$, $p = 0.004$), and *Mediomastus* spp. ($R^2 = 0.13$, $d.f. = 1.48$, $p = 0.010$); and positive for *G. demissa* ($R^2 = 0.13$, $d.f. = 1.48$, $p = 0.012$) and total molluscs ($R^2 = 0.14$, $d.f. = 1.48$, $p = 0.007$).

TABLE 4

Results of hydrocarbon analyses of samples collected in September 1995 and May 1996.[a]

Location	September 1995					May 1996				
	TPH		HPH			TPH		HPH		
	Mean	Range	Mean	Range	Percent (%)	Mean	Range	Mean	Range	Percent (%)
North Atkinson Island	56.4	2–156	53.8	2–156	95	35.4	6–115	33.8	6–108	95
Middle Atkinson Island	183.6	nd-575	141.4	nd-412	77	200.0	53–316	183.4	53–291	92
South Atkinson Island	21.6	nd-84	21.2	nd-82	98	40.4	34–52	38.6	34–49	96
Cedar Bayou	4.2	nd-21	4.2	nd-21	100	49.4	27–62	46.4	27–57	94
Cedar Point	192.6	5–600	173.6	5–360	90	43.0	12–103	40.8	33572	95
CP-HP Fringe	120.2	75–181	108.8	67–159	91	53.0	28–75	53.0	28–75	100
Goose Creek	179.4	110–294	140.2	110–217	78	208.0	62–332	177.6	55–273	85
North Hog Island	1814	162–7833	1301.4	148–5452	72	234.8	51–401	208.8	48–341	89
South Hog Island	202.4	12–548	177.6	8–490	88	208.2	24–493	180.8	24–414	87
Houston Point	222.0	52–518	168.6	51–472	76	147.4	37–327	129.8	37–278	88

[a] Mean and range of concentrations, $\mu g\ g^{-1}$ or ppm dry weight, are given for both total petroleum hydrocarbons (TPH) and heavy-range petroleum hydrocarbons (HPH) for each of the ten locations we sampled. The proportion of TPH consisting of HPH (percent) also is shown. nd = nondetectable, concentration < an estimated 5 $\mu g\ g^{-1}$.

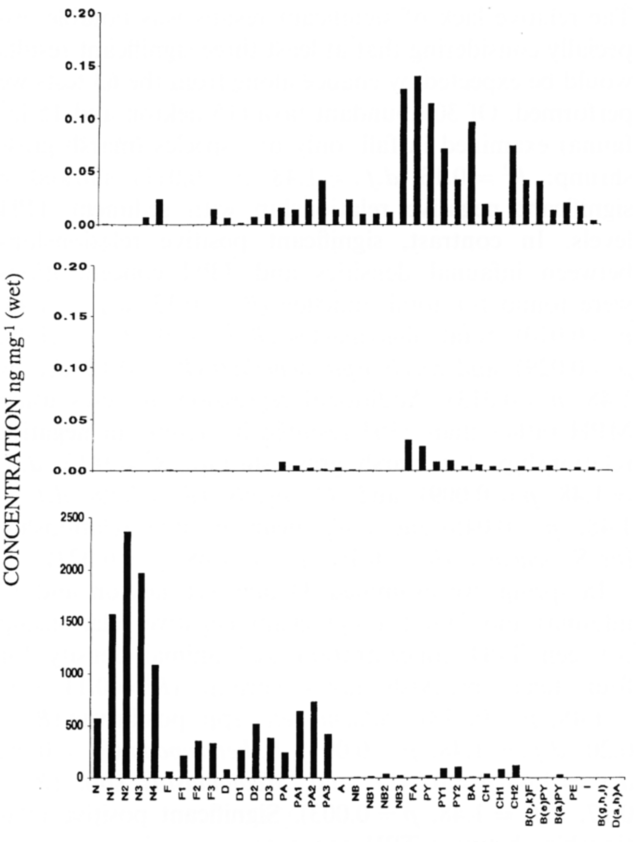

Fig. 3 Aromatic hydrocarbon profiles of selected samples analyzed by the gas chromatography/mass spectroscopy (GC/MS) method used to quantify specific aromatic hydrocarbons in sediments. Profiles are of samples taken from Hog Island north (top figure) and Hog Island south (middle figure) in September 1995; bottom figure is a profile from a sample of South Louisiana crude oil for comparison. These profiles show that oil in marsh sediments from our study area was in a highly degraded state. Key to compounds: N = naphthalenes, F = fluorenes, D = dibenzothiophenes, PA = phenanthrenes, A = anthracene, NB = naphthobenzothiophenes, FA = fluoranthene, PY = pyrenes, BA = benzoanthracene, CH = chrysenes, B(b,k)F = benzo(b,k)fluoranthenes, B(e)PY = benzo(e)pyrenes, B(a)PY = benzo(a)pyrenes, PE = perylene, I = indenopyrene, B(g,h,i)PE = benzo(g,h,i)perylene, and D(a,h)A = dibenz(a,h)anthracene.

In Stepwise Multiple Regression Analyses using 11 independent variables including either log-transformed TPH or log-transformed MPH, hydrocarbon concentration did not contribute significantly to the models for most taxa (Tables 5 and 6). In most cases, where TPH was an important variable (naked goby, white shrimp, total annelids, and *S. benedicti* in fall; *P. ligni*, *G. demissa*, and total molluscs in spring; Table 5), the relationship was positive (i.e., animal densities increased with TPH values). In addition, relationships between MPH concentration and animal densities were significant and positive in models for naked goby and white shrimp in fall and *G. demissa* and total molluscs in spring. Strong negative relationships between animal densities and hydrocarbon concentrations were rare (Tables 5 and 6); sediment hydrocarbons explained 10–20% of the variability in spring densities of brackish grass shrimp and *Palaemonetes* spp. postlarvae.

Discussion

The results of our study suggest that background levels of weathered oil in marsh sediments do *not* affect habitat use by most estuarine organisms. We found a negative relationship between animal densities and sediment hydrocarbon concentrations for only six taxa. As evident from the low R^2's for the models in each case, petroleum hydrocarbon levels in sediments could account for only a small portion of the variability in animal densities for these taxa. Furthermore, of the six taxa for which a significant negative relationship was found in one season, three (*P. intermedius*, *C. ovalis*, and *Mediomastus* spp.) showed no such relationship in the other season in which they were collected; the other three taxa (*Palaemonetes* spp. postlarvae, *P. vulgaris*, and *E. heteropoda*) showing a significant negative relationship in one season, were not numerous enough to analyse in the other season. Three of these relationships should be significant by chance; the evidence for any strong negative relationship between animal abundance and sediment hydrocarbons is lacking.

Perhaps sediment hydrocarbon levels found in upper Galveston Bay marshes are too low to affect habitat use by most species of nekton and infauna. Most sediment samples contained relatively low concentrations of petroleum hydrocarbons; these concentrations are consistent with background levels found in other highly urbanized estuaries (Overton *et al.*, 1986; Bomboi and Hernandez, 1991). The low hydrocarbon levels at our study sites were 1–2 orders of magnitude lower than the average value of 2.5 mg g^{-1} that Nance (1991) reported was needed to depress populations of benthic organisms in a small bayou connected to the Galveston Bay estuary.

Chromatographic profiles derived from the TPH analyses suggest that much of the contamination was derived from highly degraded refined oil products such as fuel oil, crankcase oil, and mineral oil that are typically found in urban runoff (C. B. Henry, pers. obs.). The highly degraded state of these sediment hydrocarbons also may have contributed to our results. Weathered petroleum consists mostly of the heavy fraction hydrocarbons that are much less bioavailable, and therefore, less acutely toxic than the light fraction contained in non-weathered petroleum and refined oil. Estuarine animals, therefore, may not have avoided these sediments in upper Galveston Bay because they are relatively non-toxic. Even though oil may initially reduce the use of intertidal habitats by aquatic organisms (Sanders, 1978; Burns and Teal, 1979; Maccarone and Brzorad, 1995), habitat use may return to normal levels after the oil has undergone sufficient weathering (Barber *et al.*, 1995). Although densities of fishes in intertidal habitats along Prince William Sound were significantly reduced in impacted areas one year after the 1989 *Exxon Valdez* oil spill, densities were not significantly different in impacted and reference areas one year later (Barber *et al.*, 1995).

TABLE 5

Results of stepwise multiple regression analyses on log-transformed densities of abundant taxa collected September 1995 and May 1996 in drop samples and from cores using 11 independent variables.[a]

Dependent variable	Independent variables					
	Step 1	R^2	Step 2	R^2	Final	R^2
September 1995						
Nekton						
Total fishes	TEMP	0.15	TEMP (ELEV)	0.35	TEMP (ELEV)	0.35
Gobiosoma bosc	(DTE)	0.13	(DTE) TEMP	0.21	(DTE) (DO) (DEPTH) (ELEV) ORGAN LTPH	0.55
Symphurus plagiusa	DEPTH	0.17			DEPTH	0.17
Anchoa mitchilli	(STEMS)	0.21	TEMP (STEMS)	0.32	DTE TEMP DEPTH	0.44
Cynoscion nebulosus	ns				ns	
Gobiesox strumosus	ORGAN	0.10			ORGAN	0.10
Mugil cephalus	ns				ns	
Total Crustaceans	(SAND)	0.09			(SAND)	0.09
Palaemonetes pugio	STEMS	0.18			STEMS	0.18
Litopenaeus setiferus	(SAL)	0.30	(SAL) LTPH	0.42	(SAL) LTPH	0.42
Palaemonetes vulgaris	(ELEV)	0.37			(ELEV)	0.37
Callinectes sapidus	STEMS	0.18			STEMS	0.18
Palaemonetes intermedius	DEPTH	0.21			DEPTH	0.21
Rhithropanopeus harrisii	ORGAN	0.18	(ELEV) ORGAN	0.27	(ELEV) ORGAN	0.27
Farfantepenaeus aztecus	(DEPTH)	0.13			(DEPTH)	0.13
Infauna						
Total Annelids	LTPH	0.17	(SAND) LTPH	0.25	(SAND) LTPH	0.25
Oligochaetes	(SAND)	0.28			(SAND)	0.28
Polydora ligni	ns				ns	
Streblospio benedicti	(SAND)	0.25	(SAND) LTPH	0.35	(DO) (SAND) LTPH	0.41
Nereis succinea	DO	0.10			DO	0.10
Mediomastus spp.	ns				ns	
Capitella capitata	(SAND)	0.19	(ELEV) (SAND)	0.27	(ELEV) (SAND)	0.27
Hobsonia gunneri	ORGAN	0.35	(DTE) ORGAN	0.41	(DTE) ORGAN	0.41
Laeonereis culveri	(DEPTH)	0.17	(DEPTH) SAND	0.26	(DEPTH) SAND	0.26
Total Crustaceans	ORGAN	0.10			ORGAN	0.10
Corophium spp.	ns				ns	
Hargaria rapax	ORGAN	0.14	DO ORGAN	0.24	DO (DEPTH) ORGAN	0.33
Cassidinidea ovalis	ns				ns	
Total Molluscs	ORGAN	0.10			ORGAN	0.10
Texadina sphinctostoma	ORGAN	0.17	(TEMP) ORGAN	0.29	(TEMP) DO (DEPTH) ORGAN	0.51
May 1996						
Nekton						
Total fishes	(STEMS)	0.16	(STEMS) TURB	0.25	(STEMS) TURB	0.25
Brevoortia patronus	ns				ns	
Symphurus plagiusa	(SAL)	0.12	(SAL) TURB	0.20	(SAL) TURB	0.20
Leiostomus xanthurus	ns				ns	
Anchoa mitchilli	TURB	0.11	(STEMS) TURB	0.21	(STEMS) TURB	0.21
Micropogonias undulatus	TURB	0.16			TURB	0.16
Total Crustaceans	(ELEV)	0.29	STEMS (ELEV)	0.36	(SAL) STEMS (ELEV)	0.42
Palaemonetes pugio	(ELEV)	0.26			(ELEV)	0.26
Callinectes sapidus	ns				ns	
Farfantepenaeus aztecus	ns				ns	
Rhithropanopeus harrisii	(SAL)	0.20	(SAL) DTE	0.31	(SAL) DTE DEPTH	0.38
Palaemonetes pl's	(LTPH)	0.20	(SAL) (LTPH)	0.27	(SAL) (LTPH)	0.27
Dsypanopeus texana	TURB	0.17			TURB	0.17
Palaemonetes intermedius	(LTPH)	0.11			(LTPH)	0.11
Callinectes similis	(DTE)	0.12	(DTE) (STEMS)	0.21	(DTE) (STEMS) (ORGAN)	0.29
Panopeus herbstii	(TEMP)	0.20			(TEMP)	0.20
Infauna						
Total Annelids	DEPTH	0.09	TEMP DEPTH	0.17	TEMP DEPTH	0.17
Oligochaetes	DEPTH	0.26	DEPTH STEMS	0.44	(SAL) TEMP DEPTH STEMS	0.55
Capitella capitata	TEMP	0.22	TEMP TURB	0.35	TEMP TURB	0.35
Mediomastus spp.	(ELEV)	0.37	TEMP (ELEV)	0.48	(SAL) TEMP (ELEV)	0.60
Nereis succinea	(TEMP)	0.20			(TEMP)	0.20
Polydora ligni	ORGAN	0.13	ORGAN LTPH	0.23	ORGAN LTPH	0.23
Laeonereis culveri	ELEV	0.26	ELEV SAND	0.34	ELEV SAND	0.34

TABLE 5 (CONTINUED)

Dependent variable	Independent variables					
	Step 1	R^2	Step 2	R^2	Final	R^2
Eteone heteropoda	(ELEV)	0.16	(ELEV) ORGAN	0.24	(ELEV) ORGAN	0.24
Streblospio benedicti	DEPTH	0.13			DEPTH	0.13
Total Crustaceans	ORGAN	0.18	(TEMP) ORGAN	0.32	(TEMP) ORGAN	0.32
Hargaria rapax	(TEMP)	0.13	(TEMP) ORGAN	0.22	(TEMP) ORGAN	0.22
Corophium spp.	ORGAN	0.35			ORGAN	0.35
Cassidinidea ovalis	ORGAN	0.35	(TEMP) ORGAN	0.53	(TEMP) ORGAN	0.53
Gammarus macronatus	ORGAN	0.29			ORGAN	0.29
Grandidierella bonneroides	ORGAN	0.35			ORGAN	0.35
Total Molluscs	(TEMP)	0.26	(TEMP) LTPH	0.35	DTE (TEMP) (TURB) LTPH	0.50
Geukensia demissa	(TEMP)	0.30	(TEMP) LTPH	0.38	(TEMP) LTPH	0.38

[a] Salinity (SAL), distance to edge (DTE), water temperature (TEMP), dissolved oxygen concentration (DO), mean depth (DEPTH), turbidity (TURB), stem density (STEMS), elevation (ELEV), sediment organic content (ORGAN), sediment sand content (SAND), and log-transformed total petroleum hydrocarbon concentration (LTPH). At each step of the analyses, included variables are shown in order of their partial *F*-ratio in that model along with the adjusted R^2 value for the model. An ns indicates that none of the variables contributed significantly to a model. The independent variable name is shown in parantheses if the relationship is negative.

Animals also may not have avoided the marsh sediments in spite of their toxicity. In experiments where flatfishes were exposed to different levels of oil-contaminated sediments in a laboratory, fish were able to detect *and* avoid heavily oiled sediments, but did not avoid lower concentrations of oiled sediments (Moles *et al.*, 1994). In another experiment, spot *Leiostomus xanthurus* did not avoid sediments contaminated by oil nor did they alter their feeding behavior in the presence of low to moderate contaminant concentrations (Hinkle-Conn *et al.*, 1998). Foods contaminated by low to moderate concentrations of oil are readily eaten by some fishes (Christiansen and George, 1995) and crustaceans (Moles, 1999). Moles *et al.* (1994) concluded that this lack of avoidance at low concentrations may lead to long-term exposure of some organisms to contaminated sediment following a spill. More research is needed to identify levels at which oil contamination can be detected by marsh nekton and to determine whether or not contaminant concentrations that are too low to be detected are toxic.

Oils may elicit positive responses from some organisms if concentrations are not high enough to be toxic. In our study, *S. benedicti*, *P. ligni*, and total oligochaete densities were positively related to sediment oil concentrations. Other studies have documented such a response, or at least a high tolerance for petroleum by the annelids *C. capitata* (DeLaune *et al.*, 1984; Plante-Cuny *et al.*, 1993; Smith and Simpson, 1995) and *Mediomastus* spp. (Kingston *et al.*, 1995). *C. capitata*, *Mediomastus* spp., and *S. benedicti* are recognized as tolerant bioindicators of contaminated estuarine sediments (Rakocinski *et al.*, 1997). However, Bridges *et al.* (1994) showed that growth of *S. benedicti* exposed to No. 2 fuel oil was reduced; they reported that *Capitella* had a greater tolerance for oil than *Streblospio*. Studies have also shown that estuarine meiofauna have a high petroleum tolerance (DeLaune *et al.*, 1984; Smith *et al.*, 1984; Carman *et al.*, 1995). Unlike Kingston *et al.* (1995), we found that *Mediomastus* spp. densities were negatively related to sediment oil concentrations in spring. However, the relationship in spring between *Mediomastus* spp. densities and sediment petroleum hydrocarbons was rather weak ($R^2 < 0.20$), and no such relationship could be shown in an analysis of our data collected in the fall. We found no strong relationships between sediment hydrocarbon concentrations and sediment grain size or organic content. Hydrocarbon concentrations were positively related to sediment organic content (fall) and the percent of silt (spring) in sediments and negatively related to the percent of sand (fall) in sediments, but these relationships explained little variability in hydrocarbon concentrations (all R^2's < 0.13). Even so, interactions among these sediment characteristics could partially explain our findings of positive relationships between sediment hydrocarbons and infaunal densities.

Acclimation to hydrocarbon exposure may play a role in the apparent high tolerance of some animals, particularly infaunal organisms, to contaminated sediments. Animals living in such sediments are constantly exposed to petroleum hydrocarbons, and thus may be adapted to low concentrations of oil that might otherwise be toxic to the same taxa living in pristine environments. Examples of hydrocarbon acclimation may be common in highly urbanized estuaries and in estuaries near petrochemical installations or petroleum production facilities (Smith *et al.*, 1984; Carman *et al.*, 1995). However, not all species can acclimate to oil pollution. Darter goby inhabiting a salt marsh contaminated by petroleum hydrocarbons showed no such acclimation (Klerks *et al.*, 1997).

It may be possible to estimate the rate of marsh recovery from small and medium oil spills in our study area using a method described by Mills (1997) who used a first-order rate equation developed by Venosa *et al.* (1996) to describe petroleum biodegradation in a wetland at Parker's Cove. The Parker's Cove wetland,

TABLE 6

Results of stepwise multiple regression analyses on log-transformed densities of abundant taxa collected September 1995 and May 1996 in drop samples and from cores using 11 independent variables.[a]

Dependent variable	Independent variables					
	Step 1	R^2	Step 2	R^2	Final	R^2
September 1995						
Nekton						
Total fishes	TEMP	0.15	TEMP (ELEV)	0.35	TEMP (ELEV)	0.35
Gobiosoma bosc	(DTE)	0.13	(DTE) TEMP	0.21	(DTE) TEMP (DO) (DEPTH) (ELEV) LMPH	0.52
Symphurus plagiusa	DEPTH	0.17			DEPTH	0.17
Anchoa mitchilli	(STEMS)	0.21	TEMP (STEMS)	0.32	DTE TEMP DEPTH	0.44
Cynoscion nebulosus	ns				ns	
Gobiesox strumosus	ORGAN	0.10			ORGAN	0.10
Mugil cephalus	ns				ns	
Total Crustaceans	(SAND)	0.09			(SAND)	0.09
Palaemonetes pugio	STEMS	0.18			STEMS	0.18
Litopenaeus setiferus	(SAL)	0.30	(SAL) LMPH	0.39	(SAL) LMPH	0.39
Palaemonetes vulgaris	(ELEV)	0.37			(ELEV)	0.37
Callinectes sapidus	STEMS	0.18			STEMS	0.18
Palaemonetes intermedius	DEPTH	0.21			DEPTH	0.21
Rhithropanopeus harrisii	ORGAN	0.18	(ELEV) ORGAN	0.27	(ELEV) ORGAN	0.27
Farfantepenaeus aztecus	(DEPTH)	0.13			(DEPTH)	0.13
Infauna						
Total Annelids	(SAND)	0.15	TEMP (SAND)	0.23	TEMP (SAND)	0.23
Oligochaetes	(SAND)	0.28			(SAND)	0.28
Polydora ligni	ns				ns	
Streblospio benedicti	(SAND)	0.25	(DO) (SAND)	0.33	(DO) (SAND)	0.33
Nereis succinea	DO	0.10			DO	0.10
Mediomastus spp.	ns				ns	
Capitella capitata	(SAND)	0.19	(ELEV) (SAND)	0.27	(ELEV) (SAND)	0.27
Hobsonia gunneri	ORGAN	0.35	(DTE) ORGAN	0.41	(DTE) ORGAN	0.41
Laeonereis culveri	(DEPTH)	0.17	(DEPTH) SAND	0.26	(DEPTH) SAND	0.26
Total Crustaceans	ORGAN	0.10			ORGAN	0.10
Corophium spp.	ns				ns	
Hargaria rapax	ORGAN	0.14	DO ORGAN	0.24	DO (DEPTH) ORGAN	0.33
Cassidinidea ovalis	ns				ns	
Total Molluscs	ORGAN	0.10			ORGAN	0.10
Texadina sphinctostoma	ORGAN	0.17	(TEMP) ORGAN	0.29	(TEMP) DO (DEPTH) ORGAN	0.51
May 1996						
Nekton						
Total fishes	(STEMS)	0.16	(STEMS) TURB	0.25	(STEMS) TURB	0.25
Brevoortia patronus	ns				ns	
Symphurus plagiusa	(SAL)	0.12	(SAL) TURB	0.20	(SAL) TURB	0.20
Leiostomus xanthurus	ns				ns	
Anchoa mitchilli	TURB	0.11	(STEMS) TURB	0.21	(STEMS) TURB	0.21
Micropogonias undulatus	TURB	0.16			TURB	0.16
Total Crustaceans	(ELEV)	0.29	STEMS (ELEV)	0.36	(SAL) STEMS (ELEV)	0.42
Palaemonetes pugio	(ELEV)	0.26			(ELEV)	0.26
Callinectes sapidus	ns				ns	
Farfantepenaeus aztecus	ns				ns	
Rhithropanopeus harrisii	(SAL)	0.20	(SAL) DTE	0.31	(SAL) DTE DEPTH	0.38
Palaemonetes pl's	DO	0.12	(SAL) DO	0.23	(SAL) DO	0.23
Dsypanopeus texana	TURB	0.17			TURB	0.17
Palaemonetes intermedius	(LMPH)	0.15			(LMPH)	0.15
Callinectes similis	(DTE)	0.12	(DTE) (STEMS)	0.21	(DTE) (STEMS) (ORGAN)	0.29
Panopeus herbstii	(TEMP)	0.20			(TEMP)	0.20
Infauna						
Total Annelids	DEPTH	0.09	TEMP DEPTH	0.17	TEMP DEPTH	0.17
Oligochaetes	DEPTH	0.26	DEPTH STEMS	0.44	(SAL) TEMP DEPTH STEMS	0.55
Capitella capitata	TEMP	0.22	TEMP TURB	0.35	TEMP TURB	0.35
Mediomastus spp.	(ELEV)	0.37	TEMP (ELEV)	0.48	(SAL) TEMP (ELEV)	0.60
Nereis succinea	(TEMP)	0.20			(TEMP)	0.20

TABLE 6 (CONTINUED)

Dependent variable	Independent variables					
	Step 1	R^2	Step 2	R^2	Final	R^2
Polydora ligni	ns				ns	
Laeonereis culveri	ELEV	0.26	ELEV SAND	0.34	ELEV SAND	0.34
Eteone heteropoda	(ELEV)	0.16	(ELEV) (LMPH)	0.26	(TEMP) ORGAN (LMPH)	0.43
Streblospio benedicti	DEPTH	0.13			DEPTH	0.13
Total Crustaceans	ORGAN	0.18	(TEMP) ORGAN	0.32	(TEMP) ORGAN	0.32
Hargaria rapax	(TEMP)	0.13	(TEMP) ORGAN	0.22	(TEMP) ORGAN	0.22
Corophium spp.	ORGAN	0.35			ORGAN	0.35
Cassidinidea ovalis	ORGAN	0.35	(TEMP) ORGAN	0.53	(TEMP) ORGAN	0.53
Gammarus macronatus	ORGAN	0.29			ORGAN	0.29
Grandidierella bonneroides	ORGAN	0.35			ORGAN	0.35
Total Molluscs	(TEMP)	0.26	(TEMP) LMPH	0.35	DTE (TEMP) (TURB) LMPH	0.49
Geukensia demissa	(TEMP)	0.30	(TEMP) LMPH	0.37	(TEMP) LMPH	0.37

[a] Salinity (SAL), distance to edge (DTE), water temperature (TEMP), dissolved oxygen concentration (DO), mean depth (DEPTH), turbidity (TURB), stem density (STEMS), elevation (ELEV), sediment organic content (ORGAN), sediment sand content (SAND), and log-transformed mid-range petroleum hydrocarbon concentration (LMPH). At each step of the analyses, included variables are shown in order of their partial F-ratio in that model along with the adjusted R^2 value for the model. An ns indicates that none of the variables contributed significantly to a model. The independent variable name is shown in parantheses if the relationship is negative.

located on the lower San Jacinto River 15–20 km northwest of our study area, is dominated by oligohaline vegetation; estuarine species dominate the nekton and benthos, and most of these species also were taken in our study (Wood *et al.*, 1995).

Recovery rates in our study marshes should not be slower than those estimated for the Parker's Cove wetland. Two of the most important characteristics upon which recovery rates depend are sediment type (and permeability) and shore (wave) exposure. Surface sediments at Parker's Cove consist of unconsolidated silt and clay and are similar to the sediments we found at many of our study sites. Shore exposure at the two areas (Parker's Cove and our study area) differed more than sediment type. Marshes in our study area generally were more exposed to wave energy than the wetlands at Parker's Cove. This characteristic (wave exposure) of our marsh study sites may be more favorable to rapid recovery from an oil spill than at Parker's Cove.

Degradation constants (k) were calculated for a suite of petroleum analytes by following the natural recovery at the Parker's Cove wetland after the 1994 Baytown Spill (Mills, 1997). The estimated degradation constant for total resolved petroleum hydrocarbons was 0.015 d^{-1}. More than 95% of the total resolved hydrocarbons had been biodegraded in approximately 150 d following the spill, and almost complete removal of resolved petroleum components had occurred by the end of the 1-year study (Mills, 1997). This method could be used in the future, following an oil spill, to estimate marsh recovery rates from initial concentrations of oil in the marshes of upper Galveston Bay.

Marsh recovery rates also will depend on the initial toxicity and concentration of the oil, as well as sediment penetration (DeLaune *et al.*, 1990; Vandermeulen and Singh, 1994; Sell *et al.*, 1995). Recovery time should increase with increases in initial toxicity and concentrations of oil on the marsh surface. Sell *et al.* (1995) estimated that recovery of marsh vegetation required 5 years after a heavy spill. Should much of the oil penetrate deep below the marsh surface, recovery times would be substantially increased and may be unpredictable using the model of Mills (1997). A marsh may take 10 years or more to recover from very thick, smothering deposits of surface oil or subsurface penetration of oil (Sell *et al.*, 1995). Long-term persistence of oil in sediments is a direct function of sediment permeability and depth of sediment penetration according to Vandermeulen and Singh (1994).

In summary, our results show little relationship between habitat use and sediment hydrocarbons in shoreline marshes of upper Galveston Bay. Most sediment samples were contaminated with relatively low concentrations of weathered petroleum hydrocarbons. These low sediment concentrations could have contributed to our findings, either because concentration levels were too low to be toxic, or levels were toxic but too low to be detected by most organisms. Results (Mills, 1997) from a study of a wetland near our study area suggest that the natural recovery rate from a light to moderate oil spill in marshes along the upper Galveston Bay shoreline could be predicted using a first-order rate equation. Recovery rates would be substantially decreased, however, and may not be predictable by the model of Mills (1997) in cases where oil is thickly deposited on the marsh surface or with deep subsurface penetration (Sell *et al.*, 1995). Our study provides essential baseline data on sediment TPH and animal densities in the shoreline marshes of upper Galveston Bay. Given the location of our study area (i.e., proximity to major ship channel, petrochemical facilities, and petroleum pipelines), these marshes may be impacted by oil spills in the future. Data from our study will be valuable in assessing impacts of future spills to living resources in upper Galveston Bay and comparable systems.

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